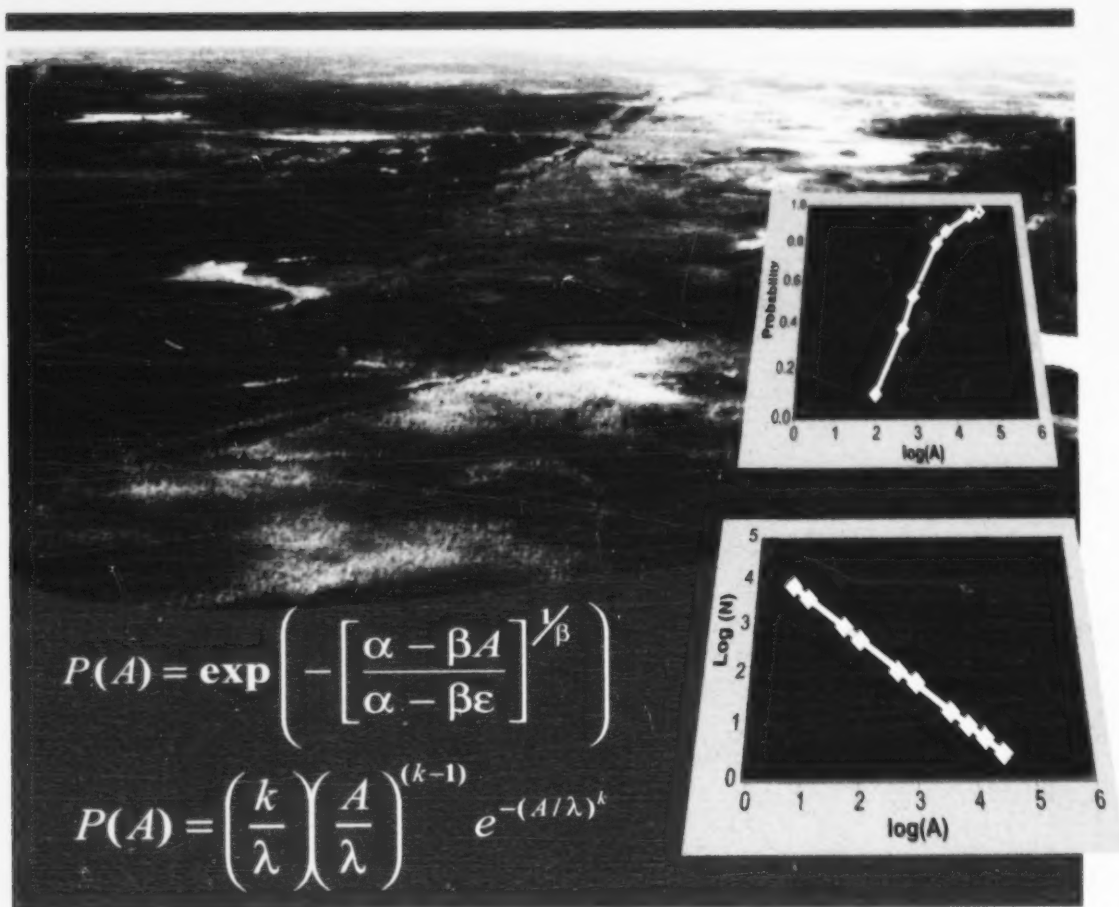


Forest Fire Size Distribution in North American Boreal Forests:

A State of Knowledge





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Abstract

The scientific, social, and economic significance of the knowledge of boreal forest fire regimes is becoming increasingly evident in North America. One synoptic indicator of fire regimes is the probability distribution of the fire size events, commonly known as the fire size distribution (FSD). For example, information about FSDs is crucial to designing long-term forest management plans that attempt to emulate forest fire regimes. We reviewed the scientific literature to examine the state of knowledge of FSDs with respect to underlying concepts, factors affecting the variability of FSD over time and space, research trends, and knowledge gaps. We found that no single probability distribution addresses all FSDs. There are reports of applications of power law, negative exponential, Pareto, truncated power law, extremal, competing-hazards model distribution types. However, the power-law family, in particular the truncated power law, seems to be most representative of the mid-range of fire event sizes. Even then, the specific parameters of these probability distributions differ among geo-climate, forest types, and human influences such as fire management strategies. Even in a given space, FSDs may differ depending on the observation period of a fire regime, as well as due to shifts in influencing factors such as climate. Therefore it is essential to understand FSDs in their spatial and temporal context. The knowledge of FSDs in literature has many gaps. Present knowledge of FSDs stems from few scattered locations and mostly the mid-range of fire sizes. The complexities of factors that affect FSDs have not been clearly understood, even in the form of hypotheses, and most of this knowledge is presently in descriptive form. Hitherto exclusive reliance on empirical methods to understand FSDs has many practical limitations, and they may be partially overcome by resorting to simulation modelling methods, especially those that are process-based. Given the limitations of the scientific knowledge, the use of FSDs in practical applications must be judicious, with clear understanding of underlying assumptions and the variability of FSDs over space and time.

Resumé

L'importance au plan économique, social et scientifique des connaissances sur les régimes des feux dans les forêts boréales devient de plus en plus évidente en Amérique du Nord. Un des indicateurs synoptiques des régimes des feux est la distribution théorique de l'étendue des feux, appelée plus communément la distribution de l'étendue des feux (DEF). Ainsi, l'information sur les DEF est primordiale à l'élaboration des plans de gestion des forêts à long terme, qui tentent d'émuler les régimes des feux de forêt. Nous avons fait le point sur la littérature scientifique pour examiner l'état des connaissances sur les DEF en rapport avec les concepts sous-jacents, les facteurs affectant la variabilité des DEF en lien avec le temps et l'espace, les tendances dans la recherche et les lacunes dans les connaissances. Nous avons constaté qu'aucune distribution théorique ne s'applique à toutes les DEF. Il existe des rapports sur les types de distribution selon les applications de la loi de puissance, de l'exponentielle négative, de Pareto, de la loi de puissance tronquée, de l'extrémalité, de modèles des risques concurrents. Toutefois, la famille de la loi de puissance, surtout la loi de puissance tronquée, semble la plus représentative de la médiane de l'étendue des feux. Même alors, les paramètres spécifiques de ces distributions théoriques diffèrent selon le géoclimat, les types de forêts et les facteurs humains comme les stratégies de gestion des incendies de forêts. Même dans un espace donné, les DEF peuvent différer selon la période d'observation d'un régime des feux, les changements affectant les facteurs d'influence comme le climat. Il est par conséquent essentiel de comprendre les DEF dans leur contexte temporel et spatial. Les connaissances sur les DEF dans la littérature comportent de nombreuses lacunes. Les connaissances actuelles sur les DEF proviennent de quelques endroits dispersés, et surtout la médiane des étendues des feux. Les complexités des facteurs qui affectent les DEF n'ont pas été clairement comprises, même sous la forme d'hypothèses, et la majeure partie de ces connaissances est sous forme descriptive à l'heure actuelle. Jusqu'ici la dépendance exclusive en des méthodes empiriques pour comprendre les DEF présente de nombreuses limites pratiques, et ces dernières peuvent être partiellement dépassées en faisant appel à des méthodes de modélisation de simulation, surtout à celles axées sur des processus. Étant donné les limites des connaissances scientifiques, l'utilisation des DEF dans les applications pratiques doit être effectuée de façon judicieuse et bien tenir compte des hypothèses sous-jacentes et de la variabilité des DEF en lien avec le temps et l'espace.

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1. Introduction

Forest fire disturbances are an essential component of some forest ecosystems, and the North American boreal forest is no exception. Forest fires could be viewed at many temporal and spatial scales. At the broader scales, cumulative fire disturbances are perceived as fire *regimes*, which describe generalized behaviour and effects of forest fires, as an aggregate of individual fire events, in larger areas, over long periods of time. There are many constituent descriptors of fire *regimes*: temporal (e.g., fire return interval), spatial (e.g., burn probability), and behavioural (e.g., intensity). Another descriptor of fire regime is the aspatial probability distribution of individual fire sizes, commonly referred to as *fire size distribution* (FSD). FSD describes the quantitative relationship between fire size and its corresponding number of occurrences in a sufficiently large forest landscape over a sufficiently long period, thereby capturing and synthesizing many elements of forest fires. Consequently, FSD is now commonly used to provide insight into forest fire regimes (Morento et al. 1998, Heyerdahl et al. 2001, Gill et al. 2003, Bergeron et al. 2004, Parisien et al. 2004).

1.1. Why fire size distribution?

Davis (1965) first used fire size classes to estimate the effect of fire management on fire *regimes*, but only in the last 20 years has the importance of FSD grown significantly, particularly for fire and forest management. In fire management, FSD is now used not only to evaluate the effect of forest fire suppression (Ward et al. 1993, Ward et al. 2001, Bridge et al. 2005, Pinol et al. 2005) but also to guide development of fuel management and fire suppression policies (Minnich 1983, Minnich et al. 1997, Chou et al. 1993). Cumming (2000) used FSD to estimate cost of fire suppression, and others have suggested using it to predict maximum fire size or large fire events based on the statistics of small- and medium-sized fires (Malamud et al. 1998, Song et al. 2001, Diaz-Delgado et al. 2004). In forest management, FSD has been used to formulate policies and strategies that guide harvest and forest management planning, particularly for emulating natural fire patterns (Strauss 1989, Hunter 1993, DeLong et al. 1998, Hawkes 1997a, OMNR 1997, DeLong 1998, Johnson 1998, OMNR 2001, Bergeron 2002, Li 2004, Perera et al. 2004a, Li et al. 2005).

FSD knowledge is also crucial for some forest fire simulation models; it is used to generate fire sizes in simulating scenarios that follow the assumed FSD (Baker et al. 1991, Baker 1992b, 1993, Niklasson et

al. 1995, Boychuk et al. 1997a, b; He et al. 1999). It has even been used as an indicator of how human settlement affects fire activities (Lefort et al. 2003). Furthermore, FSD has been used as a contextual basis in designing and maintaining natural reserves so that they contain a natural fire regime (Baker 1989, 1992a; Schneider 2001).

In spite of being researched for several decades, FSD knowledge has not been synthesized and generalized. As a result, what is known about FSDs is fragmented and dispersed in literature; its terminology is not standardized; and knowledge gaps and uncertainties are not identified. However the knowledge of FSD is becoming important for practical applications. For example, in Ontario, a clear understanding of FSD, particularly in boreal forests, is a practical necessity. Ontario annually spends up to \$150 million on forest fire management, which is significant from socio-economic, political, and ecological points of view. Also, Ontario Ministry of Natural Resources has several forest management policies that guide over 200,000 ha of forest harvest annually, based on the goal of emulating natural disturbances. These policies are formulated based on the knowledge of fire regimes, particularly natural FSD.

1.2. Goal

To address these issues, our goal in this report is to investigate and summarize the current knowledge about FSD, with special reference to how resource professionals and researchers use FSD, what methods are used to investigate FSD, and where the gaps in FSD knowledge are. The focus of this investigation, given Ontario's vantage point, was the North American boreal forest.

First, we examine those factors necessary to understand FSD; the components of FSD including definitions of terms. Second, we summarize what is reported on FSD in scientific literature, including the theoretical basis, spatio-temporal variability, causal factors, and constraints. Third, we critically review the past research on FSD, focusing on methodologies and approaches. Finally, we offer a summary of the state of knowledge on FSD, including knowledge gaps.

This review is based on a systematic and thorough review of literature (1959-2006), mostly published in mainstream scientific literature: Appendix 1 details the methods and source databases. While our primary focus was the North American boreal forest, scientific reports from other geographies were used to illustrate basic principles and address general topics.

2. Understanding forest fire size distributions

2.1. Overview

Generally, it is implied that forest fires that occur without human influence are *natural*. However, what is a 'natural' fire is a major point of contention (Suffling and Perera 2004), and therefore it is important to examine what is perceived to be natural. For example, Li et al. (1999) suggested that the term *natural conditions* refers to situations without human intervention, and Holmes et al. (2004) stated that "fires that most closely approached *natural forest conditions*" are "forest fires started by lightning". Given the increasing anthropogenic influences (generally) on forest landscape structure and composition, and (specifically) on forest fire ignition and extinguishment, all pre-European settlement fires in North America are typically regarded as natural fires, but as Suffling and Perera (2004) pointed out, even this description is inaccurate, given the influence of Aboriginal populations on forest fire ignitions.

The effect of human influence on forest fires is complex and highly variable, and therefore, the 'naturalness' of forest fires is a matter of arbitrary degree not a single entity. We attempt to illustrate this by reducing human influences to three dimensions: ignition of fires; modification of forest fuel; and suppression of fires. Using these dimensions, an absolute natural forest fire regime and human effects on a natural fire regime can be illustrated as shown in Figure 1. Accordingly, (1) the fewer the people-caused fires, (2) the less humans modify forest fuel, and (3) the less humans suppress fires, the more natural the fire regime is. So an *absolute natural fire regime* may be one without any human influences on forest conditions and fire process. In essence, while natural fire events could still occur in remote areas where human influence is absent, existence of natural fire *regimes* appears to be an impossibility, especially if one considers human influence on global and regional climate patterns. This poses a challenge to understanding 'natural' FSDs, even with assumptions, from empirical observations whether past or present. Theoretical insight and simulation modelling where what-if scenarios can be posed and assessed is probably a better alternative in understanding FSD for a varying degree of naturalness.

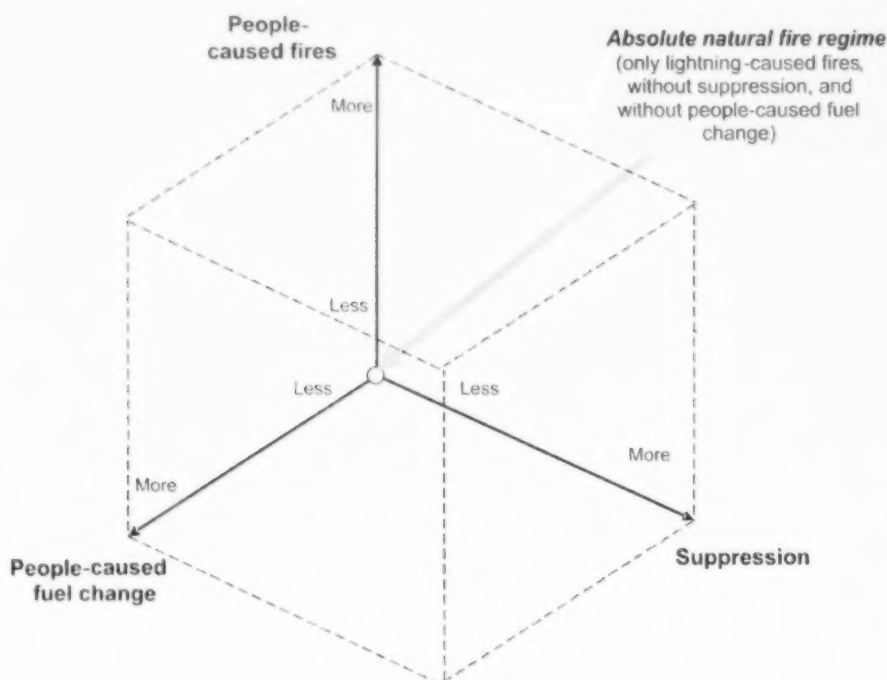


Figure 1. Three major human influences on forest fires: fire ignition, forest fuel modification, and fire suppression. Note: The axes are not orthogonal; for example, fire suppression can also cause changes in fuel.

2.2. Terms associated with forest fire size distribution

The definition of forest fire size is not consistent in literature. Many terms, such as area burned, burned area, burn area, surface burned, are commonly used interchangeably (Table 1). While the differences in these terms may appear subtle, implications to the actual fire size could be very different.

Only few authors actually defined the terms they used. For example, *area burned* (Heyerdahl et al. 2001, Cumming 2001, Rollins et al. 2001) was defined as the area within the fire perimeter. Hunter's *fire size* (1993) refers to the area encompassed by a fire's outer boundary and includes unburned patches, known as skips. The term *number of cells burned* is used to define fire sizes for raster-based fire simulation models (Boyчук et al. 1997b, Turcotte 1999, Turcotte et al. 1999, Grassberger 2002, Schenk et al. 2002, Perera et al. 2004b, Li et al. 2005, Malamud et al. 2005b). They identify burned areas without reference to perimeters, and that area contains only the cells simulated as burnt in simulation scenarios. Because the cells are pre-defined and consistent, they are easily transformed to units of area measure. The term *fire patch size* is used in some studies (Baker 1992a, Rasmussen et al. 1998, Anderson 2003b, DiBari 2003). However, this term differs fundamentally from *fire size*. DiBari (2003) defined a *patch* as a type of land cover that is uniform in composition demarcated by a perimeter; *fire-disturbed*

patch is one type of patch. Thus, a fire, especially a big fire, can create many patches. Anderson (2003b) defined a *patch* as a contiguous area of land burned that shares common physical or biological characteristics. Generally, *fire size* in literature (especially with empirical studies) refers to the total area within the fire perimeter, including unburned (residual) areas within it.

Like the definition of *fire size*, we found no consistent definition in literature for FSD, which is meant to describe the quantitative relationship between number of fires and their sizes (Cumming 2000). However, the concept of FSD is identified by many terms in literature: *wildfire size distribution* (Li et al. 1999, Cumming 2000, Schenk et al. 2000, Cumming, 2001, Schoenberg et al. 2001, Ward et al. 2001, Reed et al. 2002, Díaz-Delgado et al. 2004, Pereira et al. 2004), *fire size frequency distribution* (Chou et al. 1993, Holmes et al. 2004), *number-size distribution of forest fire areas* (Burroughs et al. 2001), *probability distribution that describes fire-size population* (Moritz 1997, Alvarado et al. 1998), *distribution of fire size* (Robertson 1972), *frequency-area (or frequency-size) distribution of fires* (Malamud et al. 1998, Malamud et al. 1999, Turcotte et al. 1999, Ricotta et al. 2001, Song et al. 2002, Malamud et al. 2005a, Malamud et al. 2005b).

The wording of these terms indicates that fire sizes and the corresponding numbers are the essential components of FSD. However, two other factors are also essential: (1) spatial extent or the size of the area within which fires have been observed (Boyчук et

Table 1. Terms used to describe forest fire size.

Term	Publication
"Fire size"	Robertson 1972, Hunter 1993, Methven et al. 1995, Hawkes et al. 1997, OMNR 1997, OMNR 2001, Diaz-Delgado et al. 2004
"Area burned"	Minnich 1983, Payette et al. 1989, Strauss et al. 1989, Chou et al. 1993, Ward et al. 1993, Delong et al. 1996, Minnich et al. 1997, Moritz 1997, Malamud et al. 1998, Alvarado et al. 1998, Weber et al. 1998, Cumming 2001, Heyerdahl et al. 2001, Johnson et al. 2001, Rollins et al. 2001, Ward et al. 2001, Lefort et al. 2003, Bergeron et al. 2004, Parisien et al. 2004, Telesca et al. 2005
"Burned area"	Malamud et al. 2005a
"Burn area"	Schoenberg et al. 2001
"Surface burned"	Morento 1998
"Number of cells burned"	Boyчук et al. 1997b, Turcotte, 1999, Turcotte et al. 1999, Grassberger 2002, Schenk et al. 2002, Li et al. 2005, Malamud et al. 2005, Perera et al. 2004b

al. 1997b, Schenk et al. 2000, Heyerdahl et al. 2001) and (2) *temporal period* or number of years fires have been observed (Rollins et al. 2001, Ward et al. 2001, Ricotta et al. 2001, Li 2004). We believe that a small study area could not only limit the number of fires but also could not encompass fires larger than the size of the study area; a short temporal extent could result in too few fires, especially large ones. As well, insufficient spatial and/or temporal extent can result in incomplete data and thus result in inaccurate determination of FSD. Contrarily, if the study landscape is too large, it is likely that derivation of a single FSD may conceal important spatial differences within (i.e., due to variations in geo-climate or land management). If the temporal period of observation of fires is too long, it may conceal periodic shifts in FSDs as a result of contextual changes (i.e., due to changes in climate or fire management policies).

As presented above, it appears necessary to define the associated terms consistently and unambiguously to standardize the derivation of FSDs and to facilitate their comparisons. First we define *fire size*. Presently, there are at least three terms used to describe *fire size* in literature: (1) burned area within the fire perimeter

including fire residuals; (2) burned area within the fire perimeter excluding fire residuals; (3) burned area of the same conditions (e.g., same forest cover type, similar fire severity). Under these descriptions, the FSD for the same fires would be different because (1) > (2) > (3). To avoid such misinterpretations, we suggest the use of terms *fire size* for (1), *area burned* for (2), and *fire patch* for (3).

We propose the term *forest fire size distribution* to replace other terms, such as fire size-class distribution, fire size frequency distribution, and fire size probability distribution. In addition, we suggest that when FSDs are reported, the researchers must provide the following minimum information: (1) the definition used for fire size, (2) the spatial extent of the study area, and (3) the temporal period of observation of fires.

2.3. Forest fire size distributions reported in literature

Many scientific publications reported FSD. Most are case studies, where observed FSDs are reported descriptively (textual descriptions). The following is a generalized summary extracted from descriptions of FSD:

Table 2. Major theoretical fire size distributions reported in literature.

Fire size distribution	Literature
A power-law distribution (without defining ranges)	Malamud et al. 1998, Song et al. 2001, Turcotte et al. 1999, Schenk et al. 2000, Ward et al. 2001, Gill et al. 2003
A power-law distribution (across a range of specified fire sizes)	Ricotta et al. 1999, Ricotta et al. 2001, Burroughs et al. 2001, DiBari, 2003, Díaz-Delgado et al. 2004, Holmes et al. 2004, Malamud et al. 2005a
Negative exponential distribution	Cumming, 2000, Li et al. 1999, Li 2000, Li 2004, Weber et al. 1998, Perera et al. 2004b, Baker 1995, Baker et al. 1991
Truncated Pareto	Cumming 2001, Schoenberg et al. 2001, Alvarado et al. 1998, Strauss et al. 1989
Segmented Pareto distribution	Robertson 1972
Extremal distribution	Moritz 1997
Approximately normal distribution	Weber et al. 1998
Competing hazards model (excluding the very largest fires)	Reed 2002
Weibull and truncated Weibull distributions	Li 2000, Pereira et al. 2004
Approximately log-normal distribution	He et al. 1999, Haydon et al. 2000

- Most fires are small, but a small number of large fires account for most of the area burned, and a large number of small fires account for a smaller fraction of the area burned (For North American boreal forest: Payette et al. 1989, Bergeron 1991, Hunter 1993, Ward et al. 1993, Methven et al. 1995, Hawkes et al. 1997a, Hawkes et al. 1997b, Johnson et al. 1998, Weber et al. 1998, Cardille et al. 2001, Johnson et al. 2001, McRae et al. 2001, Bergeron et al. 2002, Ryan 2002, Andison 2003a, Andison 2003b, Lefort et al. 2003, Bergeron et al. 2004, Li 2004, Parisien et al. 2004. For other forests: Cramer 1959, Davis 1965, Minnich 1983, Strauss et al. 1989, Chou et al. 1993, McKelvey 1996, Minnich et al. 1997, Morento et al. 1998, Haydon et al. 2000, Heyerdahl et al. 2001, Rollins et al. 2001, Vazquez et al. 2001, Diaz-Delgado et al. 2004)
- A negative relationship exists between the number of fires and their sizes (Chou et al. 1993).

While such descriptions provide information about FSD from various case studies, their information is not complete, and therefore not useful for understanding the patterns associated with FSD *in toto*, for example to describe a fire regime.

As mentioned earlier, FSD describes the *quantitative relationship* between fire size and its corresponding number of occurrences in a sufficiently large forest

landscape over a sufficiently long period, thereby capturing and synthesizing many elements of forest fires. That quantitative relationship between fire sizes and number of fires defines the complete pattern, or the probability distribution of fire size classes. Once the probability distribution is known, the dimensions (the number and the actual fire sizes) can be scaled to fit local conditions (e.g., area studied, period observed, climate, forest biome). FSD can be used to predict the probability of occurrence for any given fire size-class or range of size classes. Conversely, the fire size-classes that are likely to occur within a given probability range can also be determined.

The publications that report the nature of probability distribution of fire sizes are detailed in Table 2 and Figure 2, where 10 different FSDs (some are minor variations of others) are identified.

The distributions presented in Table 2 and Figure 2 all correspond to a negative and non-linear relationship between fire sizes and the number of fires. We illustrate those major probability distribution types below using generic scale dimensions. The first group (power-law, negative exponential, and Pareto) comprises distribution types that are largely the same, with subtle interpretative differences, and apply to all fire size classes in a fire regime. The second group includes specific probability distribution types that apply to

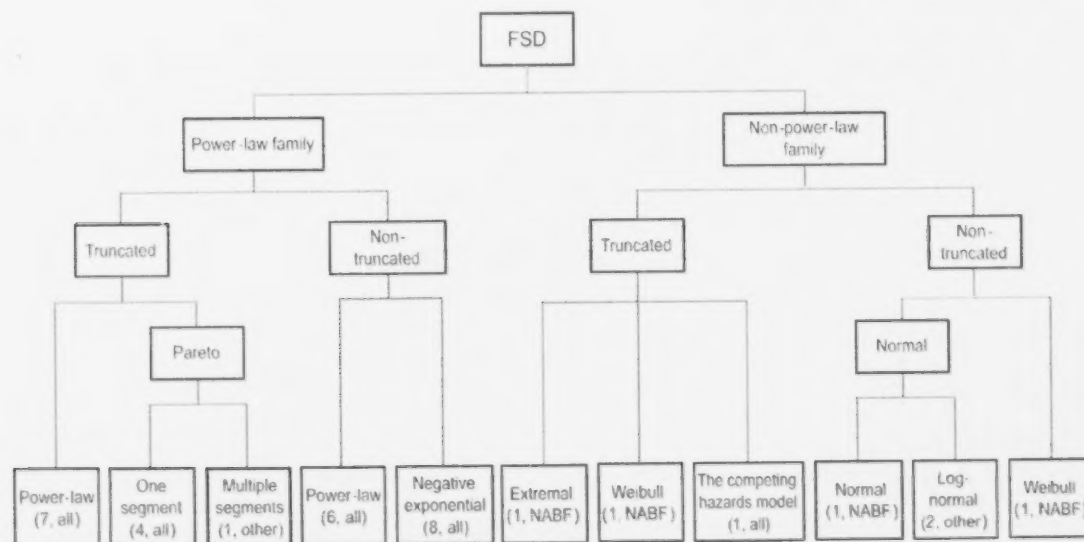


Figure 2. A grouping of major forest fire size distributions reported in publications. Note: Numbers in parentheses refer to the number of associated publications; NABF refers to North American boreal forest; "other" refers to non-NABF forests; "all" includes both NABF and "other".

selected range in fire size classes (e.g., large, rare) in a fire regime. We cannot detail some FSDs, such as the approximate log-normal distribution (He et al. 1999, Haydon et al. 2000a) because the authors did not provide a clear description. The notations in formulae given below are as proposed by respective authors. We have made only minor modifications to standardize these to facilitate comparisons.

2.3.1. Power-law distribution

The probability distribution function of a power-law distribution can be expressed as:

$$P(X=A) \sim A^{-b} \quad (1)$$

Where $P(X=A)$ is the probability distribution function, X is the variable, A is a given fire size, and b is the constant (slope).

Figure 3 shows that (a) a power-law distribution fits over the range of all fire sizes and (b) a truncated power-law distribution fits a limited range of fire sizes.

2.3.2. Negative exponential distribution

The negative exponential distribution can be expressed as:

$$P(X=A) \sim e^{-bA} \quad A > 0, b > 0 \quad (2)$$

Where $P(X=A)$ is the probability of a fire with a size of A , X is the variable, and b is the shape parameter for the negative exponential probability distribution.

2.3.3. Pareto distribution

The cumulative distribution function of a Pareto distribution can be expressed as:

$$P(X>A) \sim A^{-k} \quad (3)$$

Where $P(X>A)$ is the cumulative distribution function of a Pareto distribution, A is a given fire size and constant k is the Pareto distribution shape parameter. If $P(X>A)$ only works for part of the range of A , then it is a *truncated Pareto distribution*. If $P(X>A)$ works for several segments of the range of A , then it is a *segmented Pareto distribution*.

Negative exponential, power-law, and Pareto distributions for the logarithm of fire size are basically the same family of distributions (Reed 2002), except that each uses a different mathematical expression from a different perspective. For example, power-law distribution answers *how many fires have a size that is exactly A*. Pareto distribution answers *how many fires have a size that is greater than A*.

2.3.4. Extremal distribution

An extremal distribution (Figure 4) is usually used for extreme (large and rare) fire events (Moritz 1997), which can be expressed as:

$$P(A) = \exp \left(- \left[\frac{\alpha - \beta A}{\alpha - \beta \epsilon} \right]^{1/\beta} \right) \quad (4)$$

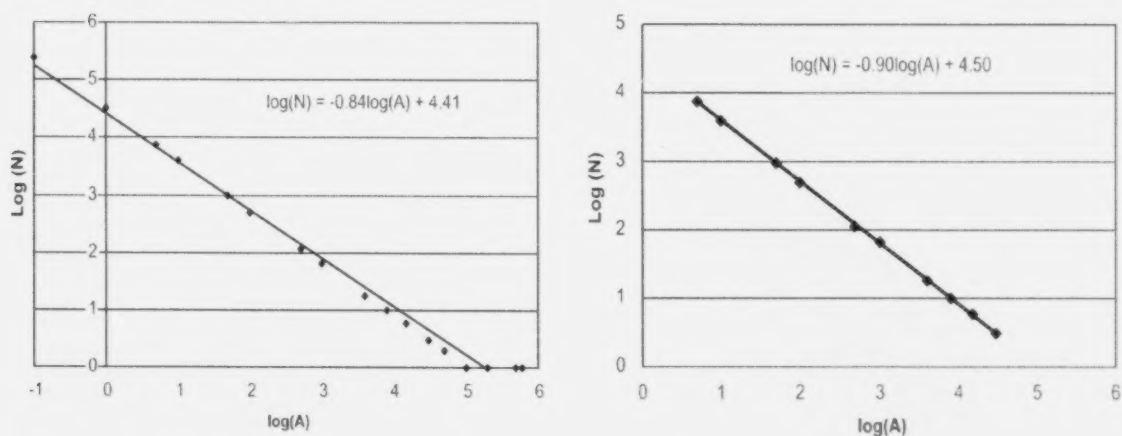


Figure 3. An illustration of power-law distribution of forest fire sizes: (a) power-law distribution, and (b) truncated power-law distribution (N is the number of fires at a given size A).

Where $P(A)$ is the cumulative distribution to estimate the probability that the largest fire in a single time period will be smaller than some specific size A . Parameters α , β and ϵ are dimensionless, and they determine the category of distributions to which $P(A)$ belongs. As the "slope" parameter β approaches 0, this distribution approaches the Extreme Value distribution. For $\beta < 0$ it is of Cauchy family, and for $\beta > 0$ it is of Weibull family. ϵ is the modal event magnitude; α measures how quickly $P(A)$ rises with the natural logarithm of time; and α/β ratio estimates the observable limits in magnitude (Moritz 1997).

A , β and ϵ must be estimated empirically using a maximum likelihood method. By creating a time series of the largest event per time event interval (e.g., the annual maximum series making up the extreme fire regime) and ranking the sample values, A_i (where i is rank of the event in the time series and the smallest has rank = 1), an estimate of the cumulative distribution can be made from the following expression:

$$P(A_i) = \frac{i}{N+1} \quad (4a)$$

Here N is the number of extreme events observed (e.g., number of extreme fire years in fire history), which is also equivalent to the highest rank. Maximum likelihood techniques are commonly used for parameter estimation from this sample distribution.

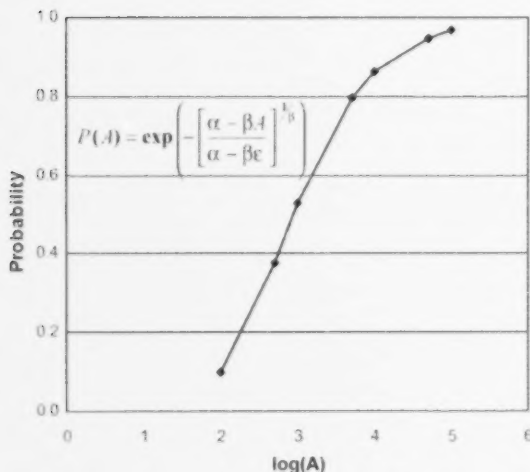


Figure 4 An illustration of the extremal distribution of forest fire sizes (A is the forest fire size).

2.3.5. The competing hazards model

The competing hazards model (Reed 2002) is developed to describe FSD for small- to medium-sized fires (excluding very large fires). It can be expressed as:

For a hazard rate of the form:

$$\rho(A) = aA^{-b} + ce^{-dA} \quad (5)$$

Where $\rho(A)$ is the hazard rate, A is the fire size, a , b , c , d are parameters that can be estimated using maximum likelihood method.

Fire size has a probability distribution function:

$$P(A) = a(A^{-b} + \theta e^{-dA}) \exp \left\{ -a \left[\frac{A^{1-b} - A_0^{1-b}}{1-b} - \frac{\theta(e^{-dA} - e^{-dA_0})}{d} \right] \right\} \quad (6)$$

Where $P(A)$ is probability distribution function, and $\theta = c/a$.

2.3.6. Weibull distribution

The Weibull distribution can mimic the behaviour of other statistical distributions such as the normal and the exponential. The probability density function of Weibull distribution is expressed as:

$$P(A) = \left(\frac{k}{\lambda} \right) \left(\frac{A}{\lambda} \right)^{(k-1)} e^{-A/\lambda} \quad (7)$$

where $A \geq 0$ is fire size, $k > 0$ is the shape parameter and $\lambda > 0$ is the scale parameter of the distribution.

When $k = 3$, the Weibull distribution appears similar to the normal distribution. When $k = 1$, the Weibull distribution reduces to the exponential distribution.

2.4. Forest fire size distributions in the North American boreal forest

There are only 8 scientific publications that quantitatively reported FSD in North American boreal forest, and all have been published within 5-year period (1998-2002). Weber et al. (1998), Li et al. (1999), and Cumming (2000) suggested that forest fire sizes in boreal forests of Canada follow the negative exponential distribution, while others provide more specific information.

2.4.1 Power-law distribution

Ward et al. (2001) found that fire sizes (4 -20,000 ha) during 1976-2000 in Ontario's boreal forest followed the power-law distributions with the varying slope values depending on the fire management zones. They reported a slope value of 1.127 for the Intensive Zone where all fires are aggressively suppressed (3279 fires) and a slope value of 1.254 for the Extensive Zone where only fires that occur near communities or that threaten other identified values and infrastructure are suppressed (484 fires). This means that small fires account for more total area burned than large fires in both zones. However, small fires account for proportionally more of the total area burned in the Extensive Zone compared with the Intensive Zone. Malamud et al. (1998) reported that forest fire sizes in Alaskan boreal forests followed a power-law distribution with a slope value of 1.43 based on 164 fires in 1990-1991.

2.4.2 Truncated Pareto distribution

Alvarado et al. (1998) used the truncated Pareto distribution to describe FSD for large fires (larger than 200 ha) for the province of Alberta, Canada. Based on fire history data from an 86,000 km² boreal forest area in northeastern Alberta, Cumming (2001) found that fire sizes have a truncated Pareto distribution with an upper bound, which for his study area and time period is about 650,000 ha.

2.4.3 Competing hazards model

Reed (2002) used his competing hazards model for small to large fires excluding those considered very large, but did not specify the actual size. He suggested that "power-law behaviour, at best, only holds over a limited range of sizes" for fires from different forests. However, his fire data for the boreal forest in Alberta and Canada's Northwest Territories showed that the power-law distribution fit reasonably well for a relatively large range of fire sizes.

FSDs reported from non-North American boreal forests also consist mainly of the family of power-law distributions (power-law, truncated power-law, negative exponential, segmented and truncated Pareto), with few exceptions. For example, Malamud et al. (1998) found fire sizes followed the power-law distribution in the western United States (slope ranges from 1.31-1.34) and in the Australian Capital Territory (slope ranges from 1.43-1.49). Song et al. (2001) fitted Chinese forest fire data to the power-law distribution, obtaining slope values from 1.25 to 1.30. Gill et al. (2003) found that fire-created patches (different than fire sizes as presented earlier) in Australian savannas

also follow the power-law. Some researchers also found fire sizes follow the power-law distribution based on various forest fire models that simulate self-organization characteristics of forest fires (Malamud et al. 1998, Turcotte et al. 1999, Schenk et al. 2000). Diaz-Delgado et al. (2004) reported that the power-law distribution can be applied for only the intermediate fire sizes in Spain (without giving detailed size range). Burroughs et al. (2001) found that the upper truncation value (the largest fire size that follows the power-law distribution) for the forest fires in the Australian Capital Territory is 72,500 ha, which is roughly 30% of the total Territory area. Ricotta et al. (1999, 2001) found that in the Mediterranean area where forest fires can exceed 100,000 ha, the power-law distribution was applicable to the 30 ha to 3000 ha size classes. DiBari (2003) suggested that forest fire sizes in Yellowstone National Park, the United States, followed a truncated power-law distribution without giving the size range. Holmes et al. (2004) found that forest fires in Florida followed a "piece-wise" power-law: slopes were different for small fires (0.04 to 1.44 ha), moderate fires (1.44 to 640 ha), and large fires (larger than 640 ha). Malamud et al. (2005a) suggested that forest fire sizes in each ecoregion in mainland United States exhibited excellent frequency-area power-law behaviour, with slopes ranging from 1.1 to 1.8, across fire sizes that exceeded 100,000 ha. Some researchers also fitted forest fire size data using the segmented Pareto distribution (Robertson 1972 for fires in California, USA) or truncated Pareto distribution (Strauss et al. 1989 for southern California and Baja region; Schoenberg et al. 2001 for Los Angeles County, California) without giving details. An exception is that Moritz used Extremal distribution to fit large fires in California, the United States.

According to literature, forest FSDs are more likely to follow a truncated power-law in both North American boreal forests and other forests, for a wide range of fire sizes, geographies, and human influences. The slope values of the power-law distributions of fires sizes are landscape specific, varying greatly over time and space caused by numerous factors. However, the present body of literature is small, geographically scattered, and not well linked.

2.5. Spatial and temporal variability of forest fire size distributions

Variability in forest FSD manifests itself either as a change to different FSD type (e.g., from negative exponential to normal distribution) or a change in the parameter(s) of the existing distribution type (e.g., the slope value of a power law distribution).

Spatially, FSDs may vary due to regional geo-climate (Malamud et al. 2005a), local climate and topography (DeLong 1998), location of the landscape (Chou et al. 1993, Hunter 1993, Ward et al. 1993, Ricotta et al. 2001, Ward et al. 2001, Anderson 2003a, Anderson 2003b, Lefort et al. 2003, Díaz-Delgado et al. 2004) and forest cover, and hence fuel type (Payette et al. 1989, Bergeron et al. 2000, Holmes et al. 2004). In some instances the spatial variability of FSD is a result of differences in fire management strategies (Ward et al. 1993, Ward et al. 2001). The spatial variability of FSD also depends on the size of the study area. For example, as mentioned above, a small study area can limit the number of large fires and exclude those larger than the study area, thereby affecting the estimates of FSD.

In general, FSDs change through time. To examine its temporal variability, we arbitrarily divided the literature on FSD studies into 2 groups based on the length of the period examined: (a) up to 20 years and (b) over 20 years. This is based on the assumption that forest cover types and climate of the studied areas do not change significantly within 20 years. There is considerable evidence in the literature that FSD changes even within a period of 20 years (but most did not describe how FSD changed over time) (Cramer 1959, Robertson 1972, Van Wagtenonk 1986, Morento et al. 1998, Díaz-Delgado et al. 2004, Pereira et al. 2004). Cramer (1959) found that from 1944 to 1956 in western Washington and western Oregon, the number of fires increased with an average rate of 37 fires per year, but the fires had become smaller and were less likely to reach 5 ha than in previous years. However, no publications offered insight into how and why the FSDs changed except Van Wagtenonk (1986) who reported that the increase in fire sizes in the western slope of the central Sierra Nevada Mountains in California was caused by changes in fire management policies. Only Davis (1965) reported that he did not observe the temporal change in FSD.

Not surprisingly, most publications that report fires observed for longer than 20 years mention that FSDs changed over time, except Malamud et al. (2005a) who reported that basically no change in FSD was found in continental United States over a 31-year period (1970-2000). Díaz-Delgado et al. (2004) reported that in Catalonia, Spain, over 24 years (1975-1998) the number of fires decreased overall, but the number of large fires increased through the study period. Cumming (2000) found that FSD in the boreal forest in northeastern Alberta varied greatly from year to year over 33 years (1961-1993). Niklasson (2000) reported a counteracting trend in fire size over 760

years in the European boreal forest – the number of fires per unit area and time increased 10-fold between the period 1350-1650 and the mid-1800s (1840-1860), whereas the proportion of the area burned per unit time increased only 4-fold. Other publications that reported FSD change without giving details include: over 35 years in Ontario's boreal forest (Ward et al. 2001), over 40 years in British Columbia, Canada (DeLong 1998), over 40 years in China (Song et al. 2001), over 60 years (1930-1989) in the boreal forest in Ontario (Weber et al. 1998), over 65 years in New Brunswick, Canada (Methven et al. 1995), and over 76 years in Ontario, Canada (Bridge et al. 2005).

Few publications offered insight into how and why the FSDs changed. Weber et al. (1998) suggested that "modified or selective fire suppression of this sort results in a negative exponential distribution which favours smaller fire size classes. Not actioning fires will result in a fire size class distribution approaching normality, with large to very large fires common". As described earlier, Ward et al. (2001) found that in Ontario's boreal forest during 1976-2000, fire sizes (4 to 20,000 ha) followed power-law distribution with the varying slope values depending on the fire management zones: the slope value was 1.127 for the Intensive Zone and 1.254 for the Extensive Zones. This not only suggests that fire suppression causes a spatial difference in FSD but also a temporal difference if fire management policy changes during the study period for a forest landscape.

No literature specifically addressed spatial heterogeneity of FSD within study areas. This may be because data were not sufficient or the researchers had already stratified the landscapes into different study areas to homogenize FSDs depending on their research objectives. For example, Minnich (1983) and Minnich et al. (1997) reported FSDs in the chaparral of southern California and northern Baja California stratified by different fire management policies, as did Ward et al. (2001) in Ontario's boreal forest.

In summary, it appears that FSDs vary over time and space but little is provided in reports of FSD about how they change and what and how the causal factors drive such changes. Thus, it is necessary to examine the fundamental factors that affect FSD.

2.6. Factors that influence observed forest fire size distributions

The cause and cessation of a single forest fire event is an extremely complex geo-physical-chemical process. Since a complete description of these processes is beyond the scope of this review, we refer readers who

are not familiar with the basic steps (i.e., how fires ignite, spread, and extinguish) to syntheses such as Johnson (1996) and Johnson and Miyanishi (2001).

A myriad of interacting factors influence FSD. However, the basic components of FSD are simple: number of fires and their sizes in a given area over a given time period. Consequently, all factors that directly affect each fire occurrence (determine the number of fires) and fire behaviour (determine the sizes of fires) can be deemed factors that influence FSD. In addition, some factors may act as overall determinants that modify fire sizes (e.g., size and shape of the study area, spatial barriers such as water bodies) and are considered spatial constraints.

We grouped these factors and constraints into short and long term, mainly depending on whether changes in forest cover (forest succession) are affected. Figure 5 illustrates the factors that influence and constrain FSD and their linkages.

2.6.1. Short-term factors/constraints

Short-term factors include factors that influence fire occurrence and fire behaviour directly, and determine FSD together with spatial and temporal constraints. The relationships between FSD and short-term causal factors and constraints can be described by the following expressions:

$$FSD = F[(W, T, F), (FM, PF, FS)]$$

$$FSD \in C_{spatial} \quad (8)$$

Where W , T , and F are weather, topography/terrain, and composition and spatial configuration of fuel and non-fuel (land cover types), respectively. FM , PF , and FS are irreversible forest cover modification by human activities, people-caused fire occurrence, and forest fire suppression, respectively. $C_{spatial}$ is the spatial constraint of fire spread and refers to geometry (size, shape, boundary conditions) of the study area that may limit forest fire spread. These constraints do not affect fire spread but they could limit fire sizes.

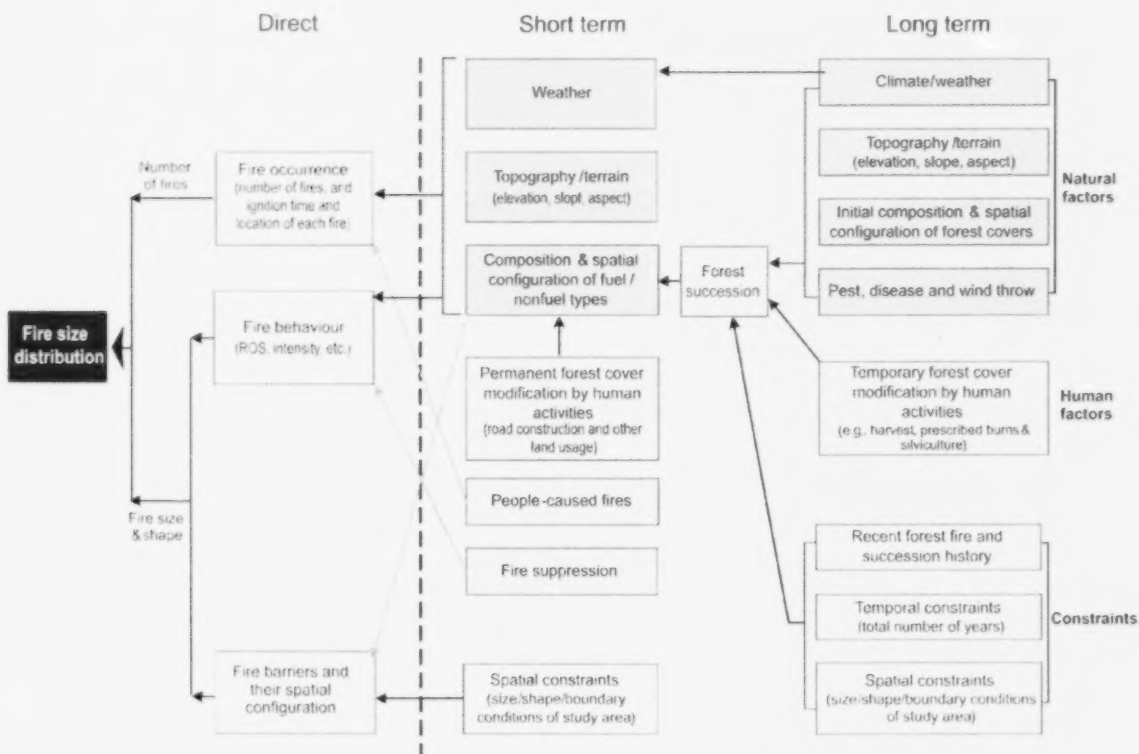


Figure 5. An abstraction of the major causal factors of forest fire size distributions.

Natural factors

Weather

The influence of weather on fire occurrence and behaviour is well studied, and copiously reported in fire science literature (e.g., Forestry Canada, Fire Danger Group 1992, Johnson 1996, Flannigan and Wotton 2001). Without repeating the details of forest fire-weather mechanics, we assert that synoptically weather conditions affect fire occurrence by controlling fire ignitions through lightning strikes as well as moisture content of fuel; fire size (Heinselman 1981) by controlling fire behaviour through moisture content of fuel, wind speed and direction; and burn time of a fire through moisture content of fuel; thus affecting FSD (Hunter 1993, Minnich et al. 1997, Malamud et al. 2005a). For example, Cramer (1959) found that number of fires is positively correlated to the total number of rainless days in national forest lands in western Washington and western Oregon.

Topography/Terrain

Topography, also referred to as *terrain* (Reed et al. 2002) and *physiography* (Hunter 1993), incorporates elevation, slope and slope aspect. Once more, the direct influence of topography on fire behaviour by controlling fire rate of spread is well articulated in fire science literature, and is considered an important factor by those who report on FSD (Heinselman 1981, Minnich 1983, Van Wagtenonk 1986, Chou et al. 1993, Hawkes et al. 1997b, Minnich et al. 1997, DeLong 1998, Bergeron et al. 2004, Malamud et al. 2005a, Telesca et al. 2005).

Composition and spatial configuration of fuel and non-fuel cover types

Land cover composition (which determines fuel availability and fuel type) influences fire occurrence, and especially fire behaviour. Fire rate of spread is different in forest cover types (e.g., fires spread faster in conifer forest than in deciduous forest) and controls the final fire sizes in a given weather-topography scenario. For example, Cumming (2001) demonstrated that the expected size of a fire in boreal mixedwood forest in Alberta was positively correlated with the abundance of pine-dominated stands in the vicinity of ignition. Therefore, the overall composition of land cover types is an important factor that affects FSD (Wagtenonk 1986, Hunter 1993, Hawkes et al. 1997b, Malamud et al. 1998, Morento et al. 1998, Song et al. 2001, Bergeron et al. 2004, Malamud et al. 2005a, Telesca et al. 2005). The spatial configuration of land cover types also influences final fire sizes and therefore FSD (Malamud et al. 1998, Ricotta et al. 1999, Reed et al. 2002). For example, if the

land cover types are interspersed by deciduous forest cover and other less burnable land cover (Ricotta et al. 1999, Parisien et al. 2004) and lakes (Hunter, 1993, Bergeron et al. 2004), fire spread is hindered under not very severe burning conditions (no spot fires), thus limiting final fire sizes, leading to more small fires and fewer large fires.

Human factors

Anthropogenic influence on FSD is manifest in 3 ways: modifying land cover and fuel availability, igniting fires, and suppressing fires. Anthropogenic land uses result in both temporary and permanent changes in fuel availability, and thus affect fire behaviour. Forest harvest, for example, creates temporary gaps in fuel availability while associated road building may create permanent fire barriers and thus limit fire sizes (Malamud et al. 2005a). Forest management practices such as prescribed burns create temporary fire barriers that might limit sizes of subsequent forest fires, or even prevent fire ignitions for many years (Pinol et al. 2005). However, human settlement and activities also result in an increased number of fire occurrences due to increased propensity for fire ignitions (Morento et al. 1998). These people-caused fires differ from lightning-caused fires in location, time, and size: (a) they are usually concentrated in areas where human activities are more frequent (e.g., camping and recreation areas); (b) their temporal pattern is different from lightning-caused fires (e.g., more fires during camping season); (c) they are usually small because such fires are usually detected and reported sooner than lightning-caused fires, and thus are more likely to be suppressed before they grow large. Fire suppression is a direct anthropogenic factor affecting FSD, although this point is debated in literature (Miyanishi et al. 2001, Ward et al. 2001) with respect to boreal forest of Ontario.

According to Li et al. (2005), "fire suppression could lead to smaller fire sizes and more fire numbers per year" based on their simulation results of fire regimes in central Saskatchewan using the SEM-LAND model. On the contrary, some researchers believe that fire suppression during initial stages of fire reduces the number and frequency of large fires in many geographies: sub-boreal forest of northern British Columbia (Hawkes et al. 1997a), boreal forest of northeastern Alberta (Cumming 2005), and Mediterranean forest of southern Italy (Telesca et al. 2005). At the same time, intense fire suppression may result in fires larger than normal because of fuel build-up, for example, in boreal forest of northeastern Alberta (Cumming 2000) and Yellowstone National Park of

the United States (DiBari 2003). Fire suppression is also believed to increase the frequency of smaller fires (Malamud et al. 1998, Ward et al. 2001, Li 2004). Consequently, in a given area anthropogenic activities influence FSD considerably.

Constraints on forest fire size distributions

Spatial constraints that modify FSD in a given area include the size, shape, and boundary conditions of the study area. For example, the size of a study area limits the total number of fires that can occur in a given period. Also, if the study area is not large enough, it may limit the number of large fires included and prevent fires larger than the size of study area from being accounted, thereby imposing an artificial truncating point on the FSD observed (Boyчук et al. 1997b, Minnich et al. 1997, Schenk et al. 2000, Heyerdahl et al. 2001). Burroughs et al. (2001) pointed out that the upper truncation point in such truncated distributions is a function of the size of the study area. In addition, the geometry of the study area and the boundary conditions may also influence fire sizes. For example, Hunter (1993) reported that fire sizes tended to be smaller in areas bounded by lakes and rivers because fires that ignited in those areas were more likely to be stopped by the water bodies compared to other fires.

2.6.2. Long-term causal factors/constraints

The long-term factors and constraints that affect FSD do so mainly by affecting forest succession and weather conditions, which determine composition and spatial configuration of fuel and non-fuel cover types. The relationship between forest succession and long-term FSD factors is expressed as:

$$\text{Forest Succession} = F[(C, T, F), RF] \quad (9)$$

Subject to constraints:

$$\text{Forest Succession} \in C_{\text{long}} \quad (10)$$

$$\text{Forest Succession} \in C_{\text{spatial}} \quad (11)$$

$$\text{Forest Succession} \in C_{\text{temporal}} \quad (12)$$

where $F[(C, T, F), RF]$ is the function of forest succession; the long-term natural factors are C (long-term climate patterns), T (topography/terrain), and F (initial composition and spatial configuration of fuel and non-fuel cover types). RF is the human factor,

namely, human modification of forest cover type. Long-term constraints on FSD are represented by C_{long} , the past fire and forest succession history that affect future forest succession; C_{spatial} , the spatial constraint on FSD (the size, shape, boundary conditions of the study area); and C_{temporal} , the temporal constraints on FSD (the number of years of study).

Many researchers mention the influence of climate on FSD (Cramer 1959, Minnich 1983, Van Wagten donk 1986, Chou et al. 1993, Hawkes et al. 1997b, Moritz 1997, DeLong 1998, Malamud et al. 1998, Rollins et al. 2001, Reed et al. 2002, Bergeron et al. 2004, Li 2004, Telesca et al. 2005). Synoptic climate regulates short-term weather patterns (Johnson 1996) and the length of the fire season, which directly affect FSD. Possible changes in climate also may affect the temporal trend of FSD (Lefort et al. 2003) by changing the temporal aspects of the fire cycle (Bridge et al. 2005). Topography, initial composition and spatial configuration of forest cover types, pests and diseases, windthrow, and recent forest fire and succession history all influence forest succession (thereby fuel types) over the long term, and thus FSD.

Human modification of cover type by forest harvesting and conversion to other cover types (such as agriculture) can change FSD (Ricotta et al. 1999, Lefort et al. 2003) over the long-term by modifying the course of forest succession, and thereby changing the composition and spatial configurations of fuel types.

The observed effects of forest succession on fuel types, and therefore FSD, is limited by the number of years for which the fires are observed when constructing a FSD. For longer period, for example over 200 years, several succession cycles may occur.

It is difficult to isolate the individual effects of factors that constrain FSD, especially when researchers classify the factors differently. For example, the location of the study area (Reed et al. 2002) or the eco-region of the study area (Malamud et al. 2005a) can be a combination of climate/weather, the composition and spatial configuration of fuel types, and human activities, among others. Similarly, age class structure and composition of forest cover in a study area (Chou et al. 1993, Pinol et al. 2005) can result from a combination of factors such as harvesting, prescribed burning, and antecedent fires (Minnich 1983, Minnich et al. 1997, Cumming 2001).

2.6.3. Self-organization of forest fires

As presented above, a range of natural and human factors influence forest fire occurrence and fire behaviour, and thus FSD. However, the occurrence

of forest fires and behaviour of forest fires also affect themselves: for example, present and past fire occurrences can influence the occurrence of future fires, as reported from southern California (Minnich 1983, Minnich et al. 1997), boreal forest in northeastern Alberta (Cumming 2001), and spruce-fir and lodgepole pine forest of Yellowstone National Park, the United States (Sweeney 1983). Cumming (2001) found that in boreal forest in northeastern Alberta the expected size of a fire is negatively correlated to the abundance of previously disturbed areas. This can be explained by the findings of Niklasson et al. (2000) from a Scandinavian boreal forest. He reported that fires occurring within 15 to 20 years act as fire breaks and limit the sizes of subsequent fires. Fires of various types or intensities in different forest types also affect forest succession, thus affecting future composition and spatial configuration of forest fuel types, and in turn affecting future fire behaviour. This phenomenon is known as the *self-organization* of forest fires and some researchers argue that natural processes such as forest fires, which are controlled by complex and interdependent factors, exhibit characteristics of *self-organization* (Malamud et al. 1998, Ricotta et al. 1999), and at equilibrium follow a truncated power law FSD (Ricotta et al. 1999, Burroughs et al. 2001). Certain forest fire simulation models predict a power-law distribution of forest fire sizes under a self organized setting, but they usually include simplified simulation premises, such as non-diverse fuel, instant burn times, and fire extinction because of fuel discontinuity (Malamud et al. 1998, Turcotte et al. 1999, Schenk et al. 2000, Song et al. 2001, Malamud et al. 2005b).

As presented above, many natural and human spatio-temporal factors interactively modify (promote and constrain) fire occurrence and fire behaviour, and thereby influence FSDs. In the short-term, weather patterns and composition and spatial configuration of forest fuel types and fire barriers appear to be important modifiers of FSDs. The long-term modifiers of FSDs may include shifts in synoptic climate and forest cover succession.

3. Methods of forest fire size distribution research

Until the 1990s, few researchers conducted comprehensive studies on FSD although some studies did result in qualitative descriptions of FSD or included quantitative analyses of FSD (Figure 6). However, the improvements in remote sensing, GIS, and computing technology during the last two decades have allowed researchers to collect and analyze data related to FSD and develop and run comprehensive and complex simulation models much more efficiently. This improved technology, coupled with the increased emphasis on understanding forest fire regimes, is probably behind the surge in literature on FSD since 1990.

3.1. Research objectives

Past research studies on FSD were conducted with a variety of objectives. Most investigations focused on *characteristics of FSD* (e.g., Robertson 1972, Strauss 1989, Chou et al. 1993, Malamud et al. 1998, Li et al. 1999, Malamud et al. 1999, Ricotta et al. 1999, Cumming 2000, Schenk et al. 2000, Burroughs et al. 2001, Cumming 2001, Ricotta et al. 2001, Schoenberg et al. 2001, Reed et al. 2002, Song et al. 2002, Pereira et al. 2004, Malamud et al. 2005a, Malamud et al. 2005b), including *annual variations* (e.g., Robertson (1972), *temporal stability of FSD* (e.g., Schoenberg et al. 2001), and *extreme fire events* (Moritz 1997, Alvarado et al. 1998). Others have focused on the *causal factors of FSD*, especially fire management (e.g., Minnich 1983, Ward et al.

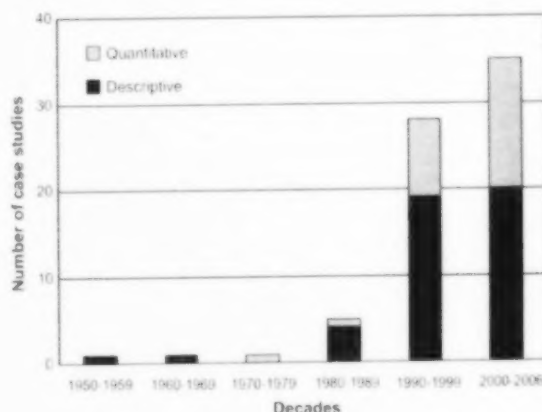


Figure 6. Temporal trend in publications that address forest fire size distributions.

1993, Ward et al. 2001, Rollins et al. 2001, Cumming 2005). For example, Minnich et al. (1997) examined how fire size and patch dynamics relate to succession processes, ignition rates, fire frequency, fire rotation periods, stand age structure, weather, burning season, and drought; Li et al. (1999) studied the relationship between fire frequency and size distribution of a fire regime under natural conditions; Song et al. (2002) investigated the effects of finite study area (the size of study area measured by the total number of cells), and probabilities of fire ignition and vegetation development on FSD; Turcotte et al. (1999) introduced a model that could explain the power-law FSD associated with self-organization; and Strauss et al. (1989) and Chou et al. (1993) examined the *methods of studying FSD*. In addition to these studies on FSD, there are many reports on *how the knowledge of FSD could be used* in emulating natural fire disturbance in forest management (Hunter 1993, OMNR 1997, OMNR 2001, Bergeron et al. 2002, Perera et al. 2004a).

3.2. Approaches of studying forest fire size distributions

To study FSD in a given study area over a specified period, the most important step is to obtain reliable and accurate information about the fire sizes and the corresponding numbers of fires. The most popular approach is to collect fire occurrence-fire size data from historical records and derive empirical relationships (Robertson 1972, Strauss et al. 1989, Chou et al. 1993, Moritz 1997, Alvarado et al. 1998, Weber et al. 1998, Ricotte et al. 1999, Burroughs et al. 2001, Cumming 2001, Ricotte et al. 2001, Schoenberg et al. 2001, Ward et al. 2001, Diaz-Delgado et al. 2004, Holmes et al. 2004, Pereira et al. 2004). However, some researchers use fire simulation methods (Li et al. 1999, Turcotte et al. 1999, Cumming 2000, Schenk et al. 2000, Reed et al. 2002, Gill et al. 2003, Malamud et al. 2005b) to predict FSDs. Other researchers applied a hybrid simulation method, which uses empirical data to support the effectiveness of their cellular automata models (Malamud et al. 1998, Malamud et al. 1999, Song et al. 2001).

3.3. Scale of forest fire size distribution research

The study extents associated with quantitative FSD research are mostly large. For example, 17 of the 25 forest landscapes studied in 8 papers (Moritz 1997, Weber et al. 1998, Ricotta et al. 1999, Cumming 2000, Cumming 2001, Gill et al. 2003, Diaz-Delgado et al.

2004, Malamud et al. 2005b) were over one million ha. As Table 3 details, some studies of FSD had a lower (minimum effective fire size) (Robertson 1972, Strauss et al. 1989, Chou et al. 1993, Alvarado et al. 1998, Cumming 2000, Cumming 2001, Schoenberg et al. 2001, Diaz-Delgado et al. 2004, Malamud et al. 2005b) and/or upper fire size limit (maximum effective fire size) (Robertson 1972, Cumming 2000, Cumming 2001, Malamud et al. 2005b).

The size of the study area is important because the number of fires included in deriving FSD is a function of the spatial extent. Also, as indicated above, the number of fires that can occur in a given study area is small for a short temporal period (number of years). It is not accurate to derive a FSD with small number of fires. In publications of FSD where the temporal study period is reported (Robertson 1972, Strauss et al. 1989, Chou et al. 1993, Moritz 1997, Alvarado et al. 1998, Malamud et al. 1998, Weber et al. 1998, Ricotte et al. 1999, Cumming 2000, Cumming 2001, Ricotte et al. 2001, Schoenberg et al. 2001, Song et al. 2001, Ward et al. 2001, Reed et al. 2002, Gill et al. 2003, Diaz-Delgado et al. 2004, Holmes et al. 2004, Pereira et al. 2004, Malamud et al. 2005b), 24 study periods were less than or equal to 40 years, 8 were between 40 and 100 years (Moritz 1997, Malamud et al. 1998, Weber et al. 1998, Ricotte et al. 2001, Schoenberg et al. 2001, Reed et al. 2002), and only 2 were over 100 years (Malamud et al. 1998, Reed et al. 2002).

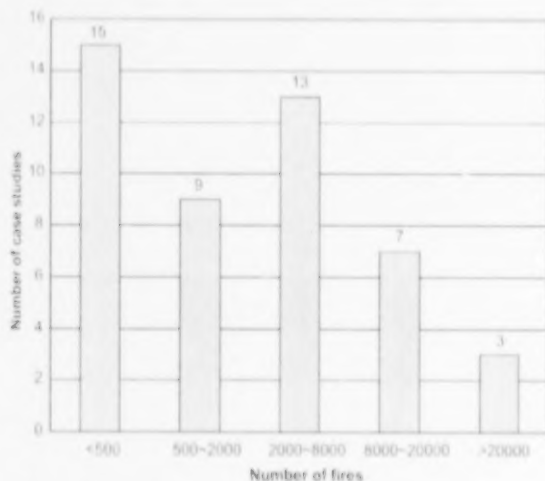


Figure 7. Number of case studies reported in literature, by number of fires used in deriving fire size distributions.

Table 3. The range of geography, temporal span, and fire sizes reported in literature.

Publication	Forest type and/or study area	Temporal span of fires (year)	Minimum fire size accounted	Maximum fire size accounted
Robertson 1972	Federal forests in California, the United States	10	About 0.1 ha	About 26,800 ha
Strauss et al. 1989	Southern California, the United States and Baja California of Mexico	15	About 0.1 ha	not reported
Chou et al. 1993	Southern California, the United States and Baja California of Mexico	10	0.04 ha	not reported
Alvarado et al. 1998	Alberta	21	200 ha	not reported
Cumming 2000	Boreal forest area in northeastern Alberta	33	9 ha	1 million ha
Schoenberg et al. 2001	Los Angeles County, California, the United States	51	About 40 ha	not reported
Cumming 2001	Boreal forest area in northeastern Alberta	19	9 ha	600,000 ha
Diaz-Deigado et al. 2004	Shrub land and forests in Catalonia, NE, Spain	24	30 ha	not reported
Malamud et al. 2005a	Continental USA	31	About 0.4 ha	About 400,000 ha

The number of fires is also affected by the spatial extent (size) of the study area. Forty-seven landscapes studied for FSD in the 13 papers provided the number of fires by landscape or region or ecoregion (Robertson 1972, Strauss et al. 1989, Chou et al. 1993, Alvarado et al. 1998, Malamud et al. 1998, Ricotte et al. 1999, Malamud et al. 2000, Cumming 2001, Ricotte et al. 2001, Schoenberg et al. 2001, Reed et al. 2002, Holmes et al. 2004, Malamud et al. 2005b) (Figure 7).

3.4. Estimating fire numbers and their sizes

As mentioned earlier, most researchers use historical survey records to obtain data on fire sizes and their corresponding numbers (Cramer 1959, Davis 1965, Robertson 1972, Van Wagendonk 1986, Baker 1989, Strauss et al. 1989, Chou et al. 1993, Hunter 1993, Ward et al. 1993, Methven et al. 1995, McKelvey et al. 1996, Hawkes et al. 1997a, Minnich et al. 1997, Moritz 1997, Alvarado et al. 1998, Weber et al. 1998, Malamud et al. 1998, DeLong 1998, Morento et al. 1998, Cumming 2000, Cardille et al. 2001, Johnson

et al. 2001, Ricotta et al. 2001, Rollings et al. 2001, Schneider 2001, Song et al. 2001, Vazquez 2001, Ward et al. 2001, Reed et al. 2002, Bergeron et al. 2004, Holmes et al. 2004, Li 2004, Parsien et al. 2004, Bridge et al. 2005, Cumming 2005, Malamud et al. 2005a, Pinol et al. 2005, Telsesca et al. 2005). However, for many regions, reliable forest fire data have been available only for the last few decades. For example, OMNR has one of the best spatio-temporal fire records, but even that data dates only to 1963.

Researchers sometimes extract the data by mapping historical fires using aerial photos (DeLong 1996, DeLong et al. 1996, Rasmussen et al. 1998, Bergeron et al. 2000, Bergeron et al. 2004) or satellite imagery (Haydon et al. 2000a). Another approach is to acquire this data by field investigations, for example collecting dendro-chronological data (Payette et al. 1989, Bergeron et al. 2000, Bergeron et al. 2004), cross-dating fire scars in dead wood and living trees (Niklasson et al. 2000), and a combination of techniques based on fire scars, abrupt changes in ring width, and cohort establishment dates (Heyerdahl et

al. 2001). Many researchers have used mixed methods to determine fire sizes and the number of fires, such as analyzing aerial photographs and sampling forest stands (Lefort et al. 2003), using both historical records and analysis of aerial photographs (Bergeron 1991, DiBari 2003, Diaz-Delgado et al. 2004), examining historical records and tree rings exposed on stumps in recent clearcuts (Wallin et al. 1996), and using historical survey records and Landsat imagery analysis (Gill et al. 2003).

Some researchers use simulation models to study FSD, without relying on empirical data on fire sizes and the number of fires, under stated assumptions of occurrence and sizes of fires (Boychuk et al. 1997b, Malamud et al. 1998, Li et al. 1999, Turcotte 1999, Turcotte et al. 1999, Schenk et al. 2000, Grassberger 2002, Reed et al. 2002, Schenk et al. 2002, Song et al. 2002, Perera et al. 2004b, Li et al. 2005, Malamud et al. 2005b).

3.5. Uncertainty in forest fire size distribution knowledge

The state of knowledge of FSD is far from perfect. One major source of uncertainties appears to be limitations associated with data: inadequacy as well as poor quality. In addition, we assert that there are weaknesses associated with the methods used in formulating FSD.

3.5.1. Data limitations

Poor quality or insufficient data make it difficult to derive reliable FSD in a given study area, as articulated by many authors (e.g., Ricotta et al. 2001, Ward et al. 2001, Telesca et al. 2005). For example, it is difficult to estimate fire occurrences (fire counts) accurately, especially over large areas. Non-detection may be common with small fires, which are difficult to detect (due to their size and short burn time) and not all small fires are regularly recorded/reported (Ricotta et al. 1999, Holmes, et al. 2004, Telesca et al. 2005). This is especially true when small fires are not considered important enough to record, and little resources allocated to detect those (Ward et al. 2001, Bridge et al. 2005). Hawkes et al. (1997b) found that the increased number of fires in recent years may be due to improved detection capabilities rather than an increase in actual fires.

Inaccuracy in delineating sizes of fire events is another major source of uncertainty. Researchers use different methods to identify fire perimeters (Haydon et al. 2000a), which can result in different boundaries for historical fires, and therefore different fire sizes (Jordan et al. 2005). The study methods described in literature

are either ambiguous or not consistent about how researchers account for merged fires; what are two merged fires to one researcher may be a single fire to another. This inconsistency can introduce considerable error into both the count of fires and fire size estimates. For example, treating merged fires as a single fire not only affects the total count of fires (underestimates the number), but also affect the incidence of large fires (overestimates the sizes) and number of small fires (underestimates the number). Equally ambiguous is how researchers account for spot fires (fires ignited outside the perimeter of the main fire by embers arising from within the main fire). If they are treated as separate from the original fire, many small fires will be included; otherwise, the main fire area will include the spot fire extent, obviously resulting in different FSD.

3.5.2. Methodological limitations

As mentioned above, the study periods reported in literature (i.e., the number of years for which fires are observed) vary widely but more than half are under 40 years. A shorter study period means a smaller number of fires (Ricotta et al. 1999, Ricotta et al. 2001, Ward et al. 2001, Li 2004), and may not be enough to derive reliable FSDs. As Rollins et al. (2001) pointed out, "the period of record in the fire atlases was probably too short to fully assess the effect of shifting size distributions on landscape patterns or ecosystem processes". As well, Burroughs et al. (2001) suggested that temporal limitations of collected data on forest fires may have an effect on the upper truncation point of the power-law distribution of forest fires.

Equally important are the limitations associated with sizes of study areas. As with shorter study periods, small study areas are likely to result in fewer observed fires. In addition, small study extents also limit the largest fire that can be observed. Schenk et al. (2000) indicated that the size of the study area may control the upper truncation point of the power-law distribution of forest fires. This is even true when raster-based simulation models are used to derive FSDs: the number of cells of simulated forest influence the estimates of FSD (Schenk et al. 2000, Grassberger 2002). The small number of cells means a small area, which creates the same problem as the limitations in the size of the study area, as discussed above.

While many fire simulation models besides self-organized forest fire models are reported in literature, reports of their use in FSD studies are absent. Present methodologies used in simulation modelling can introduce many errors to FSD estimates. A common source is that simulation models usually have a range

of assumptions which may oversimplify the scenarios being simulated. For example, self-organized forest fire models usually do not include parameters such as forest cover types, weather conditions, and fire barriers (Malamud et al. 1998, Turcotte et al. 1999, Schenk et al. 2000, Song et al. 2001, Malamud et al. 2005b) and they assume an instant burn time which is not reality.

Quality data for number of fires and their sizes may keep improving with advances in technology for detecting and measuring fires, as well as improvements in fire monitoring strategies. However, due to the complexity and interaction of natural and human causal factors of FSDs and the large spatial extent and long temporal period required to empirically study FSDs, it is an arduous task to fully comprehend and standardize FSDs under various conditions. For the same reasons, it is difficult to understand the complex mechanisms and causal relationships by relying on empirical information. However, spatially explicit process-based simulation models that simulate the physical processes of forest disturbances (fires, pest and disease, and windthrow), forest succession, and other natural processes or human activities, such as harvesting, might be helpful for exploring and gaining insights on FSDs under what-if scenarios. This approach may not only avoid the limitations of spatial and temporal extent associated with relying solely on empirical observations, but also enable isolating and understanding the relative significance of causal factors.

4. Summary

4.1 State of knowledge

Over the past 10 years, interest in forest fire size distributions (FSD) has grown considerably, both among researchers who investigate the occurrence and extent of fires, and the various forest management professionals who either attempt to develop and implement fire management policies or develop and implement policies to emulate fire disturbances with forestry practices. This interest is aided by progress in forest fire data capture and management technology as well as advances in computing and simulation modelling. The main approaches for investigating FSD are collecting empirical information on forest fires based on various cartographic and field methods (the more popular, traditional approach), and simulation modelling of forest fire scenarios under various empirical assumptions, process-based knowledge (an emerging approach), or their combination (a potential

approach). Both approaches have specific advantages and disadvantages, and therefore the FSDs derived and reported in literature must be evaluated against the validity and limitations of the associated methodological approaches.

According to the scientific literature, many theoretical distributions have been tested and fitted for FSDs. The most common appears to be the power-law distribution family (which include the power law, negative exponential, and Pareto distributions). The FSDs observed in the North American boreal forest may be best represented by the truncated power-law distribution. The reason for this power-law behaviour of FSD may be the self-organization characteristic of forest fire over sufficiently large areas and long time periods: patterns of past forest fires influence future fire occurrences and fire behaviour by controlling spatial distribution of forest fuel (assuming climate does not change). The reasons for the truncation (exclusion of mostly extreme sized fires, which are too small or too large) are not clear, but it may be an artefact of the limitations of empirical study methods. The upper truncation may be due to study areas being too small and/or study periods too short to include very large fires. The lower truncation may be due to data recording limitations associated with smaller fires (which are usually not detected and documented). The slope in the power-law distributions is an indicator of the fire regime: if the absolute slope value is smaller than 1, then (relatively) larger fires mostly account for the total area burned, and if it is larger than 1, then (relatively) smaller fires mostly account for the total area burned. Many factors influence the occurrence and behaviour of forest fires, which are the primary components of FSDs. Therefore, no single FSD can be generalized (type, slope, and truncation points) in time or space: FSDs vary among forest landscapes, geographies, climates, and as a result of human influence.

4.2. Knowledge gaps and uncertainties

The knowledge of FSD in scientific literature is far from unified. The studies described in publications are singular and isolated to the extent that even the basic terms and study methods are not consistent. Most importantly, there have been no attempts at unifying and synthesizing the knowledge of FSD, and formulating hypotheses about their causal factors and spatio-temporal variability. While it is obvious that FSDs are a direct function of forest cover, physiography, climate/weather, as well as human influences, little research effort has been put toward explaining these relationships. For example, we do not clearly know why forest fire size follows certain power-law

Table 4. Some topical areas and questions for future research on fire size distributions (FSDs).

Topical area	Research questions
Concepts	• Are occurrences and sizes of fires spatially independent? • Are properties of fire size distributions hierarchically nested, and what causes the differences? • To which major assumptions used in deriving probability distributions are FSDs most sensitive? • Which aspects of 'natural' fire disturbances are different from/similar to aspects of 'anthropogenic' fire disturbances with regard to FSDs?
Methods	• What is the effect of period of observation on FSDs derived? • What is the effect of the extent studied on FSDs derived? • Under what assumptions do simulated FSDs compare well with, and differ significantly from, empirically derived FSDs?
Causal factors	• How and when does fire suppression influence FSDs? • How does fuel modification (i.e., forest and fire management activities) influence FSDs? • What is the relationship between shifts in synoptic climate on FSDs under simulated conditions?

distributions (or other distributions) and how they are self-organized. As well, we are uncertain of the effect of many methodological limitations, whether empirical or simulation, on derived FSDs.

Consequently, whether in designing further research or formulating forest management policies and practices users of the knowledge of FSD must be cautious: special attention must be placed on limitations of methods. For example, with FSDs derived from empirical data, the scope of the investigation (length of the period for which fires have been observed and area of the study) and resolution of data (with respect to detecting small fires) and the degree of human influence on forest landscapes (directly through suppression and ignition, and indirectly through modifying fuel types) must be understood, and use of the FSD must be in that context. Similarly, with FSDs

derived from simulation models, the assumptions, premises, and constraints of modelling methods must be clearly understood to properly use the knowledge. Some of the uncertainties associated with present knowledge may be addressed by concerted and unified effort by researchers focusing on research questions similar to those listed in Table 4.

These present limitations notwithstanding, we anticipate the research interest and the user demand for knowledge on FSD will escalate. In primarily fire-driven biomes, such as the North American boreal forest, many ecological processes and economic uses, and ultimately its socio-ecological sustainability depends on how well we understand and manage the fire disturbance regime.

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Appendix 1.

Method of literature search

The objective of our literature search was to locate all scientific literature on forest fire size distributions, primarily in the North American boreal forest.

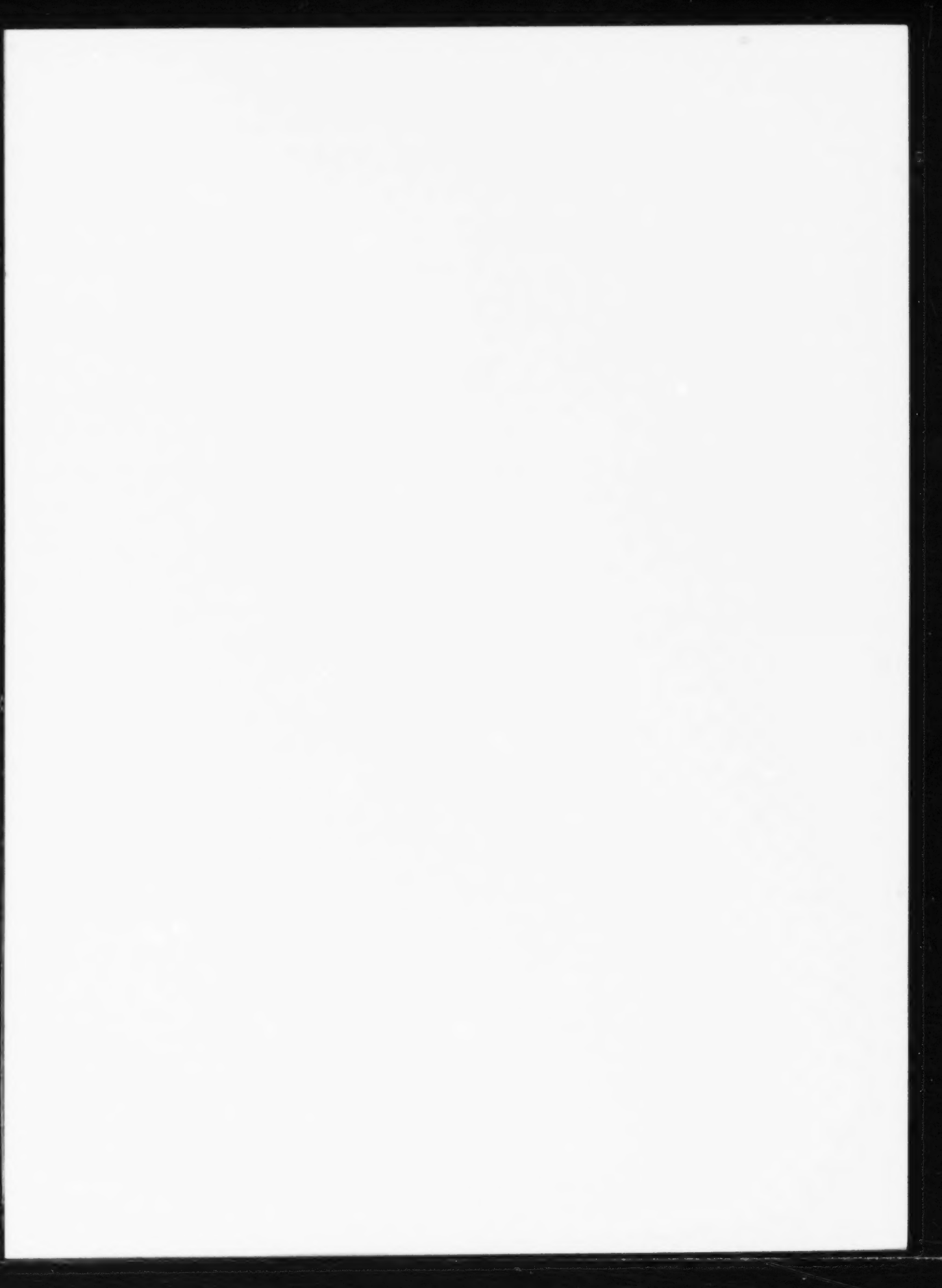
The key words used in search were: *fire, fire size, fire frequency, fire patch size, fire area burned, fire burn area, fire burned area, fire cycle, fire regime, fire history, fire distribution, fire size class, age class, wildfire size, wildfire area burned.*

The databases searched included: ISI web of science; Canadian Forest Service library network; Canadian Forest Service website: http://bookstore.pfc.cfs.nrcan.gc.ca/EMP/07-08-PUB_WebOrder_FF5&FORMAT=SEARCH.HTML&-NEW; Ontario Ministry of Natural Resources library services (internal site and database):

<http://mnr.on.ca/mnr.gov.on.ca/spectrasites/library/libraryhomepage.cfm>; Fire Ecology Database: <http://www.ttrs.org/info/fedrintro.htm>; Canadian Theses search engine: <http://amicus.collectionscanada.ca/54-bin/Main/AdvSearch?coll=18&l=0&v=1>; US Forest Service publication database: <http://www.treesearch.fs.fed.us/>; Scholar Google: www.scholar.google.com

Through the keyword search, we located over 1300 publications, which were narrowed to about 800 by reviewing their abstracts. Of this, only 99 publications (see literature cited) were useful for this report given their full content.

The body of scientific literature reviewed for this report consists of journal papers (including 1 submitted paper), books, book chapters, technical reports, and research notes.



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